



1N-20
391130

TECHNICAL NOTE

D-336

AN EXPLORATORY STUDY OF THERMOELECTROSTATIC POWER
GENERATION FOR SPACE FLIGHT APPLICATIONS

By Benjamin H. Beam

Ames Research Center
Moffett Field, Calif.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON

October 1960

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

TECHNICAL NOTE D-336

AN EXPLORATORY STUDY OF THERMOELECTROSTATIC POWER
GENERATION FOR SPACE FLIGHT APPLICATIONS

By Benjamin H. Beam

SUMMARY

A study has been made of a process in which a solar heating cycle is combined with an electrostatic cycle for generating electrical power for space vehicle applications. The power unit, referred to as a thermoelectrostatic generator, is a thin film, solid dielectric capacitor alternately heated by solar radiation and cooled by radiant emission. The theory of operation to extract electrical power is presented. Results of an experiment to illustrate the principle are described. Estimates of the performance of this type of device in space in the vicinity of earth are included. Values of specific power of several kilowatts per kilogram of generator weight are calculated for such a device employing polyethylene terephthalate dielectric.

INTRODUCTION

Light weight sources of electrical power will always be desirable for many applications but in a space vehicle the requirements for light weight power are probably more critical than in any other application. The tremendous energy needed to place a unit mass in space necessitates careful choice of auxiliary power systems for communication and guidance (refs. 1 and 2). Another area of great future interest and concern lies in the application of electrical power plants to propulsion systems (refs. 3 and 4).

Recognition of the importance of the weight of the electrical power generating system has led to a study, at the Ames Research Center, for means to accomplish significant improvements in specific power. One particularly attractive method is the conversion of solar radiation energy into electrical energy through a thermal and an electrostatic cycle. Such a generator is called a thermoelectrostatic generator in

this report. This method and some estimates of the improvements in specific power that might be realized by use of this method are described in this report.

ANALYSIS

General Performance Considerations

A promising future application of electrical power generating units is in connection with propulsion of space vehicles by the use of electrical energy to accelerate a propellant mass. A competitive situation thus exists between such a system and other propellant reaction systems such as the chemical rocket used at the present time. It is of interest to inquire what criteria can be used to determine the conditions under which electrical propulsion systems will become attractive compared with the chemical rocket. Studies of this indicate that a comparison cannot be made on the basis of specific impulse alone since the specific impulse can be chosen more or less arbitrarily with electrical systems. There is, however, an optimum value of specific impulse I_{sp} which is related to the specific power of the electrical power generating system β and the time interval over which the thrust acts τ_p . If it is assumed that the propulsion system will be operated under conditions which will permit the maximum ratio of useful load W_L to initial weight W_0 , the optimum value of specific impulse $(I_{sp})_{opt}$ can be shown to be (appendix A)

$$(I_{sp})_{opt} = \sqrt{\frac{\beta \tau_p}{g}} \quad (1)$$

where g is the acceleration due to gravity at earth. It is apparent from this that the most effective utilization of high specific impulse for short intervals of time will correspond with the highest possible values of specific power β . For this optimum condition the ratio of thrust F to initial weight W_0 becomes

$$\left(\frac{F}{W_0}\right)_{opt} = \frac{\beta}{2gI_{sp}} \left(1 - \frac{W_L}{W_0}\right) \quad (2)$$

which indicates that the most effective utilization and highest values of thrust-to-weight ratio correspond to the highest values of specific power.

Again, from a slightly different point of view the mass ratio of any electrical rocket, not necessarily optimized but characterized by

A
4
1
5

ERRATA

NASA Technical Note D-336

AN EXPLORATORY STUDY OF THERMOELECTROSTATIC POWER GENERATION FOR SPACE FLIGHT APPLICATIONS

By Benjamin H. Beam
October 1960

On page 4, in the last paragraph and on figure 1, replace the word "battery" by "variable voltage source."

On page 8, θ should be in degrees instead of radians, therefore delete " π " and insert " 180° " where it occurs. This rescaling will not affect figures 3, 4, and 7, for which units of η are taken to be $^\circ\text{K}^{-3}\text{-deg}^{-1}$.

On page 13, line 3, delete "39 watts per square meter" and insert "7 watts per square meter." On line 5, delete "3 percent" and insert "1/2 percent."

In figure 8, in the abscissa scale, delete "5, 10, 15 revolutions per second" and insert, respectively, "1, 2, 3 revolutions per second." In the ordinate scale, delete "10, 20, 30, 40 watts per square meter" and insert, respectively, "2, 4, 6, 8 watts per square meter." At the end of the figure title, add ".... and for a film thickness of 1.2 microns."

In the abscissa scale of figure 9, delete "5, 10, 15 revolutions per second" and insert, respectively, "1, 2, 3 revolutions per second." At the end of the figure title, add ".... and for a film thickness of 1.2 microns."

the general parameters I_{sp} , τ_p , and β , can be expressed as

$$\frac{W_l}{W_o} = 1 - \frac{F}{W_o} \left(\frac{g I_{sp}}{\beta} + \frac{\tau_p}{I_{sp}} \right) \quad (3)$$

For vertical take-off from earth F/W_o must be greater than 1 by some increment. Thus it necessarily follows from equation (3) that

$$\frac{g I_{sp}}{\beta} < 1 - \frac{\tau_p}{I_{sp}} - \frac{W_l}{W_o} \quad (4)$$

or, for the most optimistic conditions of $\frac{\tau_p}{I_{sp}} \rightarrow 0$, $\frac{W_l}{W_o} \rightarrow 0$

$$\beta > g I_{sp} = v_{ex} \quad (5)$$

where v_{ex} is the exhaust velocity.

This relation provides a convenient basis for technical comparisons. It will be noted that the dimensions of specific power are those of a velocity. Also the specific impulse of a rocket is a measure of its exhaust velocity. Equation (5) then expresses the condition that, for thrust-to-weight ratios to exceed 1, the specific power of the electric system must exceed the exhaust velocity (measured in the same units). For example, an exhaust velocity of 10,000 feet per second may be assumed for a chemical rocket (corresponding to a specific impulse of about 300 sec). The specific power of an electric system of the same thrust-to-weight ratio must therefore exceed 10,000 feet per second. In terms of the more familiar index of kilowatts per kilogram, 10,000 feet per second converts into approximately 30 kilowatts per kilogram. Against this requirement it is immediately apparent that the specific power of present power units is about three orders of magnitude too low (refs. 3 and 4).

It is against this background of discouragingly low specific power that electrical systems are characterized as "low thrust" systems. Their utility is presently limited to those applications where low thrust and long propulsion times are usable. An equally strong case could be made for the importance of high specific power in other space vehicle applications such as communication and control. In the analysis that follows the specific power of a thermoelectrostatic generator is recognized as the most important performance parameter and calculations are directed primarily at the evaluation of this parameter.

Characteristics of a Thermoelectrostatic Generator

The electrostatic cycle.— Electrostatic conversion of energy into electrical energy, as it applies to a wide variety of electrostatic machinery and phenomena, can be described as follows: A capacitor C_1 is initially charged to a difference of potential V_1 so that the charge on the capacitor q becomes

$$q = C_1 V_1 \quad (6)$$

The source of the charge, for example a battery, is then removed. The charge on the plates will remain constant while the capacitance is changed to a new value C_2 . The new voltage V_2 becomes

$$V_2 = \frac{q}{C_2} = \frac{C_1}{C_2} V_1 \quad (7)$$

The energy E stored in the capacitor, originally equal to

$$E_1 = \frac{1}{2} C_1 V_1^2 \quad (8)$$

becomes

$$E_2 = \frac{1}{2} C_2 V_2^2 \quad (9)$$

The change in electrical energy is equal to the work done in changing the capacitance (for example, forcing the plates apart in the case of a parallel plate condenser)

$$\delta E = E_2 - E_1 = \frac{1}{2} C_2 V_2^2 - \frac{1}{2} C_1 V_1^2 = \frac{1}{2} C_2 V_2^2 \left(1 - \frac{C_2}{C_1} \right) \quad (10)$$

This is the maximum electrical energy that can be withdrawn by a suitable electrical circuit.

The idealized schematic arrangement is shown in figure 1. The sequence of operations assumed for a cycle of charging and discharging the capacitor starts with the closing of the switch S_1 when the capacitance is at C_1 . When the capacitor is fully charged S_1 is opened and the capacitance is changed to C_2 . The switch S_2 is then closed and part of the charge returns to the battery through the load resistor R . For the idealized circuit shown, the charge returned to the battery when the capacitance is at C_2 is the same as that withdrawn on the next succeeding cycle as the capacitance is returned to C_1 , so that the net drain of charge from the battery is zero after the capacitor is once charged. If this cyclic process is repeated f times per second, the possible power output to the load becomes

$$P = \frac{1}{2} f C_2 V_2^2 \left(1 - \frac{C_2}{C_1} \right) \quad (11)$$

Equation (11) represents the power output of the class of electrostatic devices represented by figure 1.

From equation (11), it is seen that the dielectric properties of the device, and the maximum energy stored in the machine during a cycle, are involved in the term

$$E_2 = \frac{1}{2} C_2 V_2^2 \quad (9)$$

If the capacitance is achieved through parallel plate electrodes separated by a dielectric, and fringing or edge effects are neglected, the energy stored per unit area of capacitor, ψ , becomes

$$\psi = \frac{1}{2} \frac{C_2}{A} V_2^2 = \frac{1}{2} K \frac{V_2^2}{l} \quad (12)$$

where K is the permittivity of the dielectric of thickness l and area A . This energy per unit surface ψ , changed by a factor $1 - (C_2/C_1)$ each cycle, and repeated f times per second results in the maximum power that can be developed per unit area of capacitance.

The change in capacitance during a cycle can be accomplished in a number of ways. In space, the most readily available form of energy is radiant thermal energy from the sun. One can imagine a number of different mechanical arrangements in which this thermal energy can be used to vary the spacing between capacitor plates. The method to be considered here, however, is that changes in capacitance can be produced directly by changes in temperature of the dielectric material. The combination of these effects in one device is referred to in this report as a thermoelectrostatic generator.

The thermodynamic cycle.— Consider a capacitor arrangement consisting of a solid dielectric in the form of a thin cylindrical film, with thin metallic electrode sections on the inner and outer surfaces of the film, as shown in figure 2. Each section consists of a lengthwise strip the width of which is small compared to the circumference of the cylinder. Then electrical conditions at each strip can be considered a function of angular position only, isolated from conditions on adjacent strips. For an area element of the cylinder dA exposed to incident radiant energy from the sun on one side, the increment of heat absorbed dQ_{α} in a time interval dt is given by

$$dQ_{\alpha} = \alpha \sigma T_s^4 \left(\frac{r_s}{r} \right)^2 \sin \theta \, dA \, dt \quad (13)$$

where α is the absorptivity, σ the Stephan-Boltzmann radiation constant, T_s an effective temperature of the sun's surface (about 6000°K), r_s the effective radius of the solar disk, r the radial distance from the sun, and θ is the angle between the radiation from the sun and the absorbing surface. If a background temperature of space is assumed to be near absolute zero, and if the small area of the celestial sphere covered by the sun is ignored, heat radiates in the amount dQ_{ϵ} from the area element dA in the time interval dt given by

$$dQ_{\epsilon} = \epsilon \sigma T^4 dA \, dt \quad (14)$$

where ϵ is the surface emissivity and T the surface temperature. Heat is conducted along the film between adjacent unit areas of different temperature in the amount dQ_{γ}

$$dQ_{\gamma} = \gamma \frac{l}{R} \frac{dT}{d\theta} \, dt \quad (15)$$

where γ is the thermal conductivity of the film, l its thickness, and R the radius of the cylinder in figure 2. The ratio of the heat conducted between unit areas dQ_{γ} to the heat radiated per unit area dQ_{ϵ} becomes

$$\frac{dQ_{\gamma}}{dQ_{\epsilon}} = \frac{\gamma(l/R)(dT/d\theta)}{\epsilon \sigma T^4} \quad (16)$$

For temperatures from a hundred to several hundred degrees Kelvin, and the low values of thermal conductivity representative of electrical insulators, the above ratio is roughly of the order of l/R . For film thicknesses of a few microns and a radius of the order of meters the heat conducted along the skin is completely negligible in determining the thermodynamic equilibrium and is therefore ignored.

On the other hand, the ratio of the heat conducted across the film to the inner surface, dQ_{γ}' , to the radiated heat per unit area is

$$\frac{dQ_{\gamma}'}{dQ_{\epsilon}} = \frac{\gamma(\Delta T/l)}{\epsilon \sigma T^4} \quad (17)$$

where ΔT is the temperature difference between the inner and outer surface. For the same range of temperatures and thermal conductivities

considered above, it is seen that heat is conducted across the film quite readily with temperature differences ΔT of less than 1° . The interior surface is assumed to have a metallic reflective coating with a low emissivity coefficient. In this way heat transferred by radiation from the interior can be neglected. This inner metalized film serves as one electrode in the capacitor. Similarly, the outer surface is metalized to form the other electrode with a surface having a high emissivity and absorptivity. These electrode surfaces are considered to have been applied by evaporation methods so that their thickness can be less than 1000 angstroms. Thus their weight, heat capacity, and thermal conductivity are negligible compared with that of the dielectric material.

The above considerations permit the simplifying assumption that thermodynamic equilibrium is established from the incident thermal radiation from the sun, thermal radiation into space, the bulk properties of the dielectric material, and the useful electrical energy withdrawn from the system

$$dQ = dQ_\alpha - dQ_\epsilon - dE \quad (18)$$

where dE is the electrical energy being drawn from the system at any instant. This increment is dependent on the externally applied voltage as inferred from equation (10). For a system of low efficiency it is apparent from elementary considerations that dE (the useful energy) will be smaller than either dQ_α (the energy absorbed) or dQ_ϵ (the energy rejected), at least on an integrated basis over a complete cycle. It can also be surmised that since heat is absorbed only on the side of the cylinder exposed to the sun and rejected on all sides including the side in shadow from the sun, dQ (the energy stored in the cylinder material) is of the same order of magnitude as dQ_α and dQ_ϵ over portions of the cycle. Thus the efficiency of the system depends on a relatively small difference in film temperature, proportional at any instant to the useful energy withdrawn and the heat capacity of the material. In the following it is assumed that $dE = 0$, and this simplification permits the calculation of the temperature distribution along the film from which a calculation of the electrical power output can be made. From the power output the efficiency and an order of magnitude of dE can be calculated and the validity of neglecting dE in equation (18) confirmed later.

Equation (18) then becomes

$$dQ = dQ_\alpha - dQ_\epsilon \quad (19)$$

and equation (19) can be used to solve for T as a function of θ . From the bulk properties of the dielectric material, ρ being the density, C_p the specific heat capacity at constant pressure, and equations (13) and (14)

$$\rho l \, dA \, C_p J \, dT = \alpha \sigma T_e^4 \sin \theta \, dA \, dt - \epsilon \sigma T^4 dA \, dt \quad (20)$$

J is the Joule equivalent and T_e is defined as an equivalent, black body, subsolar temperature at a distance r from the sun

$$T_e = T_s \sqrt{\frac{r_s}{r}}$$

The cylinder is assumed to be rotating uniformly, $\theta = 2\pi ft$,

$$dT = \frac{\alpha \sigma T_e^4}{2\pi f \rho l C_p J} \sin \theta \, d\theta - \frac{\epsilon \sigma}{2\pi f \rho l C_p J} T^4 d\theta \quad (21)$$

If ϵ and C_p are assumed constant over the temperature range of interest, a constant parametric coefficient can be defined,

$$\eta = \frac{\epsilon \sigma}{2\pi f \rho l C_p J} \quad (22)$$

Then the solution to the nonlinear differential equation

$$\frac{dT}{d\theta} + \eta T^4 = \eta \left(\frac{\alpha}{\epsilon} \right) T_e^4 \sin \theta \quad 0 < \theta < \pi \quad (23)$$

represents the temperature distribution as a function of incidence angle for the side of the cylinder exposed to the sun. For the side of the cylinder in shadow, the incident radiation is zero, and

$$\frac{dT}{d\theta} + \eta T^4 = 0 \quad \pi < \theta < 2\pi \quad (24)$$

Although equation (24) can be solved directly, the initial conditions are determined from the solution of equation (23), so that the complete solution for T as a function of θ from 0 to 2π involves the solution of equations (23) and (24) together. The general solution involves a transient where T , starting from any assumed initial value, changes with each succeeding cycle until an equilibrium or steady-state condition is achieved. The steady-state solution is established after the decay of the initial transient to yield the variation of T with θ such that T at $\theta = 2\pi$ returns to the value of T at $\theta = 0$.

Equations (23) and (24) have been solved by numerical integration on an IBM 704 computer for a range of values of the parameters

$(\alpha/\epsilon)^{1/4} T_e$ and η . Two steady-state solutions showing the variation of temperature with angular position are presented in figure 3 for values of the parameter η of 10^{-9} , 10^{-10} , and 10^{-11} . For a cylinder of film having given surface radiation characteristics and located at a given distance from the sun $(\alpha/\epsilon)^{1/4} T_e$ is constant and the temperature characteristics depend on the single parameter η . The temperatures of the hottest and coldest points on the film as a function of η for the two different values of $(\alpha/\epsilon)^{1/4} T_e$ are shown in figure 4. The value of 400° K corresponds approximately with calculated values of the black body subsolar temperature in the vicinity of earth. High values of η for a given film represent slow rotational frequencies of the cylinder, and low values of η represent rapid rotational frequencies. For the highest values of η shown on figure 4, the highest temperature is $(\alpha/\epsilon)^{1/4} T_e$ and the lowest temperature is about 120° K. For the lowest values of η , representing extremely rapid rotation, the entire surface approaches a uniform temperature. With the radiating area in this case being π times the effective heat absorbing area this uniform temperature becomes

$$T_{\eta \rightarrow 0} = (\alpha/\pi\epsilon)^{1/4} T_e = 0.75(\alpha/\epsilon)^{1/4} T_e \quad (25)$$

The differences in temperature that occur during a rotational cycle as indicated in figure 4 will change the dielectric constant of a section of the insulating film by a corresponding increment during each cycle. The extent of this change depends on the functional relation between capacitance and temperature for the material under consideration. Generally the relation between capacitance and temperature cannot be represented by a simple function for the dielectrics of interest in this application. This prevents a simple theoretical relation between the solution for temperature in figure 4 and that for power output in equation (11). However, a graphical relationship between temperature and capacitance can be used to proceed from figure 4 to equation (11).

The parameter η is composed of a number of terms characterizing the physical properties of the dielectric and the rotational frequency f . For any value of η in figure 4 a corresponding value of f can be calculated, provided density, thickness, and heat capacity of the capacitor film are known. Likewise, the power developed depends on the energy stored in the capacitor, represented by the parameter ψ . Limitations on ψ are imposed by the maximum voltage which the dielectric can withstand without sparking over. Realistic estimates of the properties of a thermoelectrostatic generator must therefore be based on the consideration of specific materials, the properties of which are not predictable from theory at the present time.

APPLICATIONS

General Considerations on Dielectrics

It has been assumed in the discussion thus far that the dielectric in the capacitor was a solid and the main structural component in the rotating film. Before proceeding to the detailed consideration of a solid material, it is worthwhile to reflect on some of the additional considerations which would be important in the application of this technique of power generation to a space vehicle.

Liquid or gases, which might be attractive on the basis of their dielectric properties, would present severe leakage problems in a space environment over extended periods of time. The weight of the necessary containing vessels to prevent leakage would limit the specific power and penalize the performance. For this reason solid materials which would not leak or evaporate would be utilized if possible, and further discussion of liquid or gaseous dielectrics is omitted from this report.

Another dielectric of great interest for space applications is high vacuum. The excellent insulating properties of high vacuum which have been demonstrated in laboratory devices, and the possibility of operating a vacuum-insulated capacitor in the circuit illustrated in figure 1, without the need for a containing vessel in space, is worth serious consideration. Some data on the insulating properties of dielectrics, presented in terms of the energy storage parameter Ψ , are shown in figure 5 as a function of the dielectric thickness l . The shadowed region shown for high vacuum was calculated from the experimental data compiled in reference 5. Various investigators have shown that the dielectric strength of a vacuum-insulated gap depends on the type of electrode material and the manner of preparation. Thus to represent the spread of the data, Ψ in figure 5 is shown to occupy a range rather than a specific value for each electrode spacing. The value of Ψ is shown to be surprisingly constant over a range of gap spacings from a fraction of a millimeter to several meters. This experimental observation has led to some interesting theories concerning the nature of electrical breakdown in vacuum (refs. 5, 6, and 7). The wide choice of gap spacing and the promising values of Ψ have led to a variety of experimental machines to achieve high voltages or high specific power or both (refs. 8 and 9). The results of these tests can be summarized briefly by remarking that although a number of attempts have been made to develop such machines, none appear to have been successful enough to compete with other electrical power generating systems. One difficulty, apparently common to all vacuum insulated machines, is that the maximum values of Ψ presented in figure 5 for high vacuum are obtainable only with careful and elaborate methods of electrode preparation and conditioning. The form adopted for a vacuum-insulated electrostatic generator

is usually that of a rotating machine converting mechanical power to electrical. Provision for the same carefully controlled, high-vacuum conditions and freedom from contaminants is generally not feasible for a high-speed rotating machine with large electrode areas even under the best laboratory conditions. There is no doubt that development of rotating electrostatic generators has lagged because of experimental difficulties, although it could be argued that the problems of electrode contamination would not exist in space. Another factor to be considered in estimating the specific power is that the complete power system requires an additional energy conversion step from radiant or thermal energy to mechanical, and the weight of this latter step dominates the weight of the system and limits the potential gain in specific power.

A
4
1
5

These preliminary remarks on applications lead again to a consideration of the solid dielectrics assumed in the section on theory. A review of the solid materials available for consideration embraces the materials presently used in capacitor manufacture. (See, e.g., ref. 10.) From the theory it is apparent that a high-energy storage parameter ψ and an acceptable variation of capacitance with temperature is desired. Another desirable electrical property of the material is that the volume resistivity of the dielectric should be high. Consideration of the various possibilities does not lead to one material that is clearly superior to all others, but polyethylene terephthalate¹ film has been selected as a representative material of considerable promise. The properties of this material will be used in subsequent calculations illustrating the behavior of the solid dielectric type of thermoelectrostatic generator. Polyethylene terephthalate has high mechanical strength in thin films and good dielectric properties over a wide temperature range. In figure 5 the energy storage parameter ψ for polyethylene terephthalate film (calculated from the data of ref. 11) is shown to equal or exceed that of the best high vacuum. These dielectric strength properties cannot be realized under atmospheric pressure and moisture conditions, but the vacuum conditions of space should be ideal for promoting the maximum dielectric strength. The electrodes for the tests of polyethylene terephthalate described in reference 11 were evaporated metal less than 100 Å in thickness. When a localized weak spot developed in the film, an arc occurred which vaporized the surrounding electrode metal and extinguished itself. For the application considered in this report it could also be assumed that if the metallized electrodes were kept thin the capacitor film could be made self-healing from defects in the film or punctures from other sources. In the calculations that follow, a value of ψ equal to 50 Joules per square meter has been used for polyethylene terephthalate film.

Fairly complete data exist for the dielectric constant over the temperature range from 200° K to 450° K (ref. 12), and extrapolation of the data is necessary for temperatures outside this range. In

¹A polyester plastic, sold under the trade names of "Mylar" and "Terylene."

computing the variation of capacitance with temperature in figure 6 allowance has been made for change in dielectric constant and also for the thermal expansion of the dielectric. Over the range of temperature from 300° K to 430° K the calculated data have been checked with manufacturers' test data for 0.5 microfarad capacitors insulated with polyethylene terephthalate film 0.00025 inch thick (ref. 13). Other factors being equal it is apparent that the most desirable temperature range for operation of a thermoelectrostatic generator is that which will result in the largest capacitance variation.

Many dielectric materials exhibit larger variations in capacitance with temperature than that shown in figure 6. Ferroelectrics have particularly promising characteristics in this application (ref. 14) and a generator similar to the type discussed herein is described in reference 15. Although the dielectric constant of ferroelectric materials can change by orders of magnitude in a limited temperature range, their properties in other respects are not so promising. For example, the dielectric strength is lower than that of polyethylene terephthalate and the dielectric constant varies markedly with field strength as well as temperature. Since the subject is extensive and the present report is not intended to be definitive in this respect, the question of relative merit of different dielectrics will not be pursued here.

Performance of a Thermoelectrostatic Generator

For a thermoelectrostatic power unit operating at a fixed distance from the sun, T_e is a constant. For a blackened surface $\alpha/\epsilon = 1$ and thus T_e would be the maximum temperature which any portion of the film would reach. For an actual blackened metallic film such as assumed in this example it is doubtful that either α or ϵ would be equal or sufficiently close to 1.0 to neglect the difference. In fact, it may be desirable to have α somewhat greater than ϵ , as this will produce higher temperatures on the side of the cylinder exposed to the sun. The appropriate values of α and ϵ would be determined so as to operate the dielectric at the optimum temperatures for power output, and presumably the surface of the film could be prepared to provide the desired radiation characteristics (refs. 16 and 17).

The quantities f and $1 - (C_2/C_1)$ required to calculate the output power in equation (11) can be related to the parameters η and $(\alpha/\epsilon)^{1/4} T_e$ in equations (23) and (24). This is illustrated in figure 7, where the data of figures 4 and 6 have been combined and the temperature has been eliminated to show $1 - (C_2/C_1)$ as a function of η . For any given value of f , η can be evaluated and the value of $1 - (C_2/C_1)$ from figure 7 along with the energy parameter for polyethylene terephthalate from figure 5 can be used to calculate the power output per

unit area of capacitor film. Results of this calculation are shown in figure 8. Quickly comparing the indicated maximum power output of 39 watts per square meter with the incident solar energy of 1.3 kilowatts per square meter at a distance of one astronomical unit from the sun ($T_e = 391^\circ \text{K}$) results in an estimated efficiency of 3 percent and justifies the neglect of dE in equation (19).

The data on the power output shown in figure 8 were calculated for an idealized system in which internal losses of the generator were neglected. The useful power is only that portion of the generated power which remains after subtraction of the power losses due to charge leakage across the dielectric, imperfect switching, etc. Experimental data indicate that the insulation resistance of polyethylene terephthalate is decreased both by high temperature and high-voltage stress. Data are lacking for the combination of high-voltage stress and high temperature considered for the more attractive power generation conditions in figure 8, and, in the absence of these data, it is necessary to proceed on the basis of estimates. In reference 11 the conduction current through polyethylene terephthalate film at high-voltage stress is shown to be strongly affected by humidity, corona, and points of dielectric weakness in the film. Upon elimination of humidity and corona and the removal of these weak spots, the conduction current returns to a low value at high voltages roughly corresponding to the same value of insulation resistance as at low voltage. It can be argued that in the space-flight application considered, humidity and corona are eliminated as a problem, and, since the thin electrode films are self-healing, the weak spots in the film are automatically removed in operation. This view permits estimates of power loss from values of insulation resistance applicable to low-voltage conditions (ref. 13). Considering that the elevated temperatures are encountered only during a portion of the cycle as shown in figure 3, these data indicate that the leakage power loss is always less than 50 milliwatts per square $(\alpha/\epsilon)^{1/4} T_e = 400^\circ \text{K}$, and less than 2 watts per square meter for $(\alpha/\epsilon)^{1/4} T_e = 450^\circ \text{K}$. For the temperature conditions of peak power output shown in figure 8 the power loss is considerably less than the above maximums. Similarly, it can be shown that if efficient solid-state electronic devices are used for the switches indicated in figure 1, the power loss in the switches is negligible compared with the power transferred. (This ratio is ordinarily less than 1 percent for silicon diode rectifiers.) Thus the values of power per unit area presented in figure 8 are considered to be realistic estimates of values that might be obtained with a well-engineered system.

For the same values of f as assumed in figure 8, the parameter η can be reduced to a weight per unit area of capacitor film. With this and the data of figure 8, a specific power β' has been calculated for various values of rotational frequency and the results are shown graphically in figure 9.

The value of β' differs from the over-all specific power β in that the additional items of weight required for switching and control, considerations of matching the load to the generator, and structural items, have not been included in β' . It is easy to visualize that the weight of these neglected items can be considerable, and would probably be at least of the same order as the weight of the film on which the value β' is based. This would imply that the over-all specific power, β , would be of the order of half the values of β' shown in figure 9. Even allowing for this, however, potential values of β are indicated which are several orders of magnitude over the best values currently available and at least an order of magnitude better than those anticipated in the future from other methods of power generation in space (refs. 3 and 4).

A
4
1
5

Matters of electrical circuitry and structural detail have been purposely avoided in this general study. For example, the source of charge was illustrated in figure 1 as a battery although it can be shown that such a power unit employing a number of sections of capacitor film can be so arranged electronically that a battery is not required for operation. Similarly, it can be shown that careful attention in matching the load to the generator is necessary to utilize the maximum power available and that generator voltages under conditions of maximum power may be several thousand volts. It has been assumed that the rotation of the cylinder of film at the appropriate speed, and the orientation of the rotational axis with respect to the sun, can be accomplished by means of presently known techniques. The configuration suggested is that of a cigar-shaped, inflatable structure rather than the idealized cylinder considered. A meteor puncture in the film would probably not impair operation or result in serious damage; however, the cumulative effects of meteorite erosion on the thin films may prove to be important.

EXPERIMENTAL RESULTS

In this section a simple experiment will be described which illustrates the physical principles on which the study of this report is based. A section of capacitor film 1-1/4 inches wide and 6 inches long was stripped directly from a commercial capacitor. The section consisted of two adjacent layers of polyethylene terephthalate, each layer metalized on one side and 0.0005 inch thick. The capacitor section was bonded with adhesive to a light wire framework, and the exposed metalized side was painted with blueing to increase thermal absorptivity on the side to be heated. This assembly was mounted on an axis so that it could be rotated rapidly into and out of a position where the plane of the film was about 1/8 inch away from a heated copper plate (see fig. 10). A blackened thermocouple was supported on the wire framework in a position between the capacitor film and the heated plate, and approximately 1/16 inch from the plate.

As a preliminary experiment the variation of capacitance with indicated thermocouple temperature was measured. With the capacitor film held in position near the plate and the plate gradually heated, measurements were made of thermocouple temperature and capacitance. The results of these measurements are shown in figure 11 along with the variation assumed earlier for the calculations on specific power (fig. 6). The lower limiting temperature for these tests was the dew point temperature, below which moisture condensation affected the dielectric characteristics of the film. An upper limiting temperature was imposed by high leakage currents, wrinkling, and local hot spots on the film.

A 4 1 5
It may be noted in figure 11 that a difference between the expected and measured variations exists, and the slope of the expected variation is positive while the slope of the measured variation is initially negative, becoming positive at higher temperature. Also the measured percentage changes in capacitance over the temperature range of these tests was smaller than that assumed on the basis of references 12 and 13. The reasons for this are not known, but the measured variation is considered to be the appropriate variation for the generation of voltage and power with the test apparatus described. Experimental verification of specific power, etc., calculated on the basis of the assumed variation of capacitance with temperature, is not attempted herein and would depend on more sophisticated experiments.

The experiment to demonstrate the generation of electrical energy from thermal radiation was conducted using the circuit shown in figure 10. The electrical circuit is seen to be substantially that shown in figure 1 with silicon diodes substituted for the switches. In figure 12 the result of alternately exposing the film to the heated plate and then removing it is shown. The period of the oscillatory cycle of heating and cooling was about 2 seconds and the indicated thermocouple temperature varied cyclically about 20° K over a temperature range for the tests from about 350° K to 400° K. The cyclic variation of 20° in temperature was sufficient to induce a voltage on the recording oscilloscope of about 0.4 volt, as seen on figure 12, during the part of the cycle that the film was being heated. This is in the direction indicated from the measured negative slope of capacitance with temperature in figure 11. Adding the voltage drop in the silicon diode of about 0.5 volt to the 0.4 volt output results in a generated voltage of 0.9 volt from 90 volts applied to the film. This is approximately the 1 percent voltage increase indicated from the measured data of figure 11.

Other experimental arrangements using polyethylene terephthalate film, differing in geometric detail and in the method of applying the heating cycle, were tried and the results agree with those presented. In each case the voltage was observed to increase as sufficient heat was applied to the film, and to drop as the film was cooled, essentially duplicating the above experimental results. Thus, while the principle

seems clearly demonstrated in that power was generated as a result of heating and cooling a charged capacitor, the practical possibilities in terms of specific power that can be obtained with polyethylene terephthalate or other materials remain subject to further experimental study.

CONCLUDING REMARKS

Future progress in space travel will be profoundly affected by increases in the power-to-weight ratio of electrical power plants. In this report a study is presented of a power generation system for space flight applications referred to as a thermoelectrostatic generator. The system considered employs thin, light-weight films of electrical capacitor material exposed to the sun's radiant thermal energy which converts the incident heat power to electrical power in a cyclic process. Results of a simple experiment illustrating the principle are described in this report. Some estimates of the performance of this type of generator in space are presented. Indications are that values of specific power of several kilowatts per kilogram of generator weight may be possible. Since these values of specific power are two orders of magnitude over values obtainable at present, the system shows considerable promise.

Ames Research Center
National Aeronautics and Space Administration
Moffett Field, Calif., July 8, 1960

A
4
1
5

APPENDIX A

PERFORMANCE RELATIONS

Performance relations for the space vehicle with an idealized electrical propulsion system were derived on the basis of three simplifying assumptions. The first assumption is that the vehicle exhausts all its propellant with a constant specific impulse I_{sp} during a time interval τ_p , so that W_p , the total weight of propellant, becomes

$$W_p = \frac{F\tau_p}{I_{sp}} \quad (A1)$$

where F is the thrust produced. The second assumption is that the weight of the power plant is directly proportional to the jet power of the ejected propellant. For some electrical power units this is a reasonable assumption but for others the output power cannot be scaled up or down without more critical effects on the weight. In any case, however, the assumption of a linear relationship between the power output and the weight of the power generating unit W_g results in the relation

$$W_g = \frac{Fv_{ex}}{\beta} = \frac{FgI_{sp}}{\beta} \quad (A2)$$

where β is the specific power and v_{ex} is the velocity at which the propellant is exhausted. The third assumption employed for the purpose of simplifying the analysis is that all weight except that assigned to the propellant or power plant is considered useful load, W_l . This would include the weight of all miscellaneous items of structure and equipment that could not properly be charged to the weight of the power generating unit. Thus, where W_o is the initial weight of the vehicle

$$W_l = W_o - (W_p + W_g) \quad (A3)$$

The mass ratio of the vehicle becomes

$$\frac{W_l}{W_o} = 1 - \frac{F}{W_o} \left(\frac{gI_{sp}}{\beta} + \frac{\tau_p}{I_{sp}} \right) \quad (A4)$$

An optimum value of specific impulse, defined as that for which the mass ratio is a maximum, is found by differentiating equation (A4)

$$\frac{d}{dI_{sp}} \left(\frac{W_l}{W_o} \right) = 0 = \frac{g}{\beta} - \frac{\tau_p}{I_{sp}^2} \quad (A5)$$

from which

$$(I_{sp})_{opt} = \sqrt{\frac{\beta \tau_p}{g}} \quad (A6)$$

Inserting equation (A6) into equation (A4) and solving for the thrust-to-weight ratio for this optimum condition yields

$$\left(\frac{F}{W_o} \right)_{opt} = \frac{\beta}{2gI_{sp}} \left(1 - \frac{W_l}{W_o} \right) \quad (A7)$$

APPENDIX B

DEFINITIONS AND SYMBOLS

A	area
C	electrical capacitance
$C_{20^{\circ} \text{ C}}$	reference value of capacitance at 20° C
C_p	specific heat capacity of dielectric
E	electrical energy
F	total thrust of vehicle
I_{sp}	specific impulse of propellant, thrust per weight flow of propellant per unit time
J	Joule equivalent, 4184 Joule per kilo calorie
P	power
Q	heat energy
R	electrical resistance
T	absolute temperature
T_e	equivalent black-body subsolar temperature at distance r, $\sqrt{\frac{r_s}{r}} T_s$
T_s	effective temperature of solar surface
V	voltage
W_0	initial weight of vehicle
W_l	weight of useful load in vehicle
f	rotational frequency, revolutions per second, or cyclical frequency of power production, cps
g	acceleration due to gravity at earth's surface
l	thickness of dielectric

q	electrical charge	
r	radial distance from sun	
r_s	effective radius of sun	
v_{ex}	exhaust velocity of propellant from vehicle	
α	surface absorptivity	
β	specific power of electrical power unit, power output per unit weight	
β'	specific power neglecting all weight components except that of the capacitor film	A 4
γ	heat-conduction coefficient	1 5
ϵ	surface emissivity	
η	parametric coefficient (eq. (22))	
θ	angle of incidence of radiation from sun with respect to absorbing surface	
K	permittivity of dielectric	
ρ	density of dielectric	
σ	Stephan-Boltzmann radiation constant, 5.672×10^{-8} watts per meter ² deg ⁴	
τ_p	time increment over which thrust acts, sec	
ψ	energy storage per unit capacitor area (eq. (13))	

Subscripts

1	maximum capacitance
2	minimum capacitance
α	absorbed
ϵ	radiated
γ	conducted
opt	optimum

REFERENCES

1. Hibbs, Albert R., ed.: Exploration of the Moon, The Planets, and Interplanetary Space. Jet Propulsion Lab., Calif. Inst. of Tech., Rep. No. 30-1, April 30, 1959.
2. Scharla-Nielsen, H.: Space Ship Telemetry. IRE Trans. on Telemetry and Remote Control, June 1958, pp. 36-39.
3. Sutherland, George S.: Recent Advances in Space Propulsion. ARS Jour., vol. 29, no. 10, pt. I, Oct. 1959, pp. 698-705.
4. Zwick, Eugene B., and Zimmerman, Robert L.: Space Vehicle Power Systems. ARS Jour., vol. 29, no. 8, Aug. 1959, pp. 553-564.
5. Cranberg, Lawrence: The Initiation of Electrical Breakdown in Vacuum. Jour. Appl. Phys., vol. 23, no. 5, May 1952, pp. 518-522.
6. Trump, John G., and Van de Graaff, R. J.: The Insulation of High Voltages in Vacuum. Jour. Appl. Phys., vol. 18, no. 3, March 1947, p. 327.
7. Borovik, E. S., and Batrakov, B. P.: Investigation of Breakdown in Vacuum. Soviet Physics, vol. 3, no. 9, Sept. 1958, p. 1811.
8. Trump, John G.: Electrostatic Sources of Electric Power. Electrical Engineering, vol. 66, no. 6, June 1947, pp. 525-534.
9. Breaux, O. P.: Electrostatic Power Generation for Space Propulsion. Electrical Engineering, vol. 78, no. 11, Nov. 1959, pp. 1102-04.
10. von Hippel, Arthur R.: Dielectric Materials and Applications. John Wiley and Sons, Inc., New York, 1954.
11. Inuishi, Y., and Powers, D. A.: Electric Breakdown and Conduction Through Mylar Films. Jour. Appl. Phys., vol. 28, no. 9, Sept. 1957, pp. 1017-22.
12. Reddish, Wilson: The Dielectric Properties of Polyethylene Terephthalate (Terylene). Faraday Society, Transactions, vol. 46, 1950, pp. 459-475.
13. Anon.: Mylar Polyester Film. Bulletin TR-3, E. I. DuPont DeNemours and Company (Inc.), June 1955.
14. Shirane, G., Jona, F., and Pepinsky, R.: Some Aspects of Ferroelectricity. Proc. IRE, Dec. 1955.

A
4
1
5

15. Anon.: Ferroelectrics Generate Power. Res. and Dev. Dept., Electronics, vol. 32, no. 51, Dec. 16, 1959, p. 88.
16. Wilson, Raymond H., Jr.: Temperature of a Close Earth Satellite Due to Solar and Terrestrial Heating. Science, vol. 127, no. 3302, April 11, 1958, pp. 811-12.
17. Betz, H. T., Olson, O. H., Schurin, B. D., and Morris, J. C.: Determination of Emissivity and Reflectivity Data on Aircraft Structural Materials. WADC Tech. Rep. 56-222, pt. II, Oct. 1958.

A
4
1
5
2

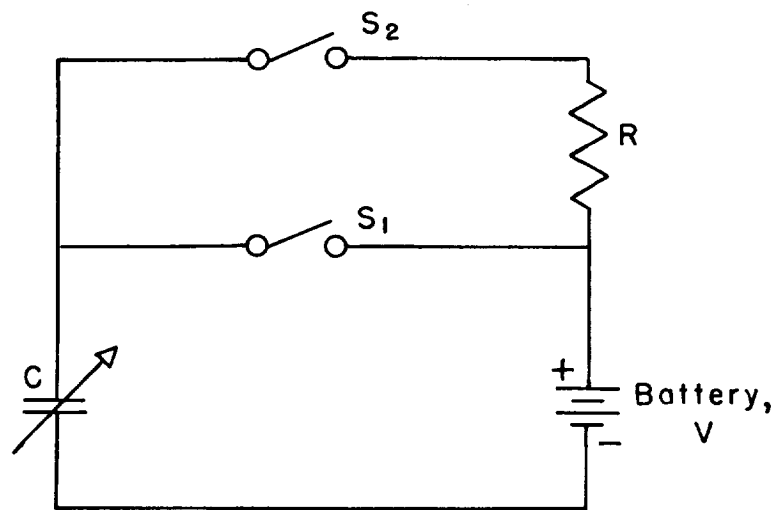
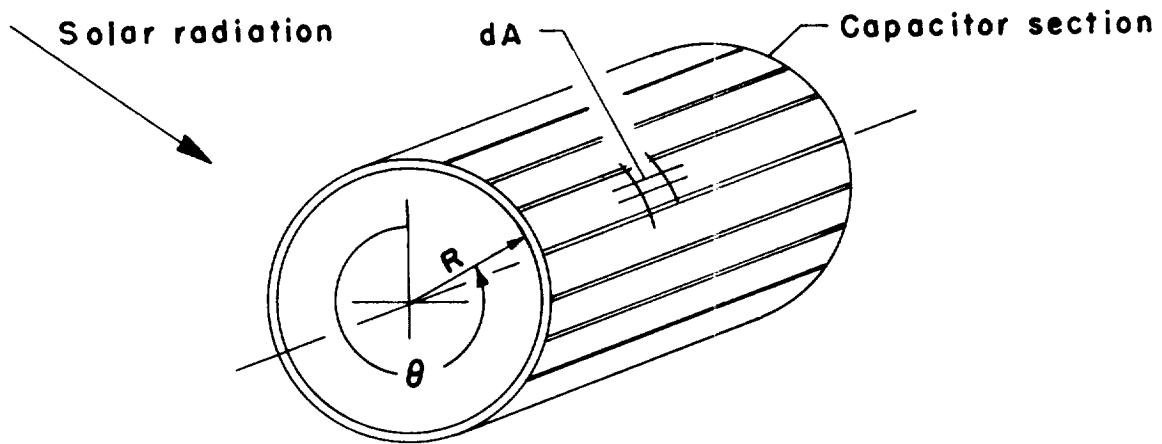


Figure 1.- Schematic diagram of idealized electrostatic generator.



(a) Overall schematic.

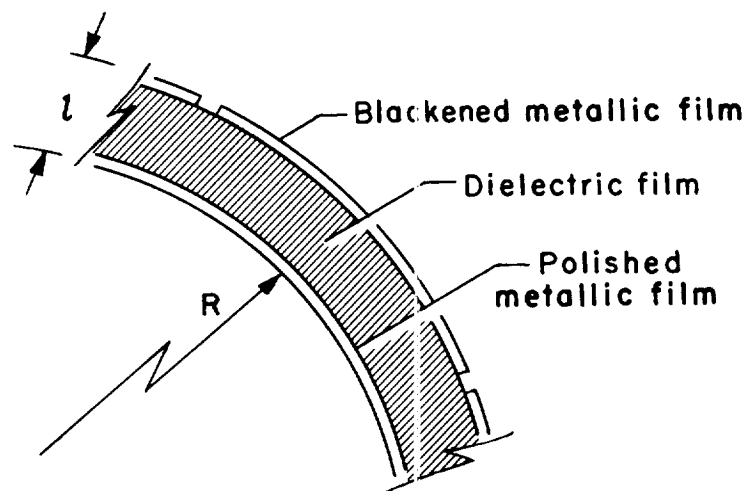
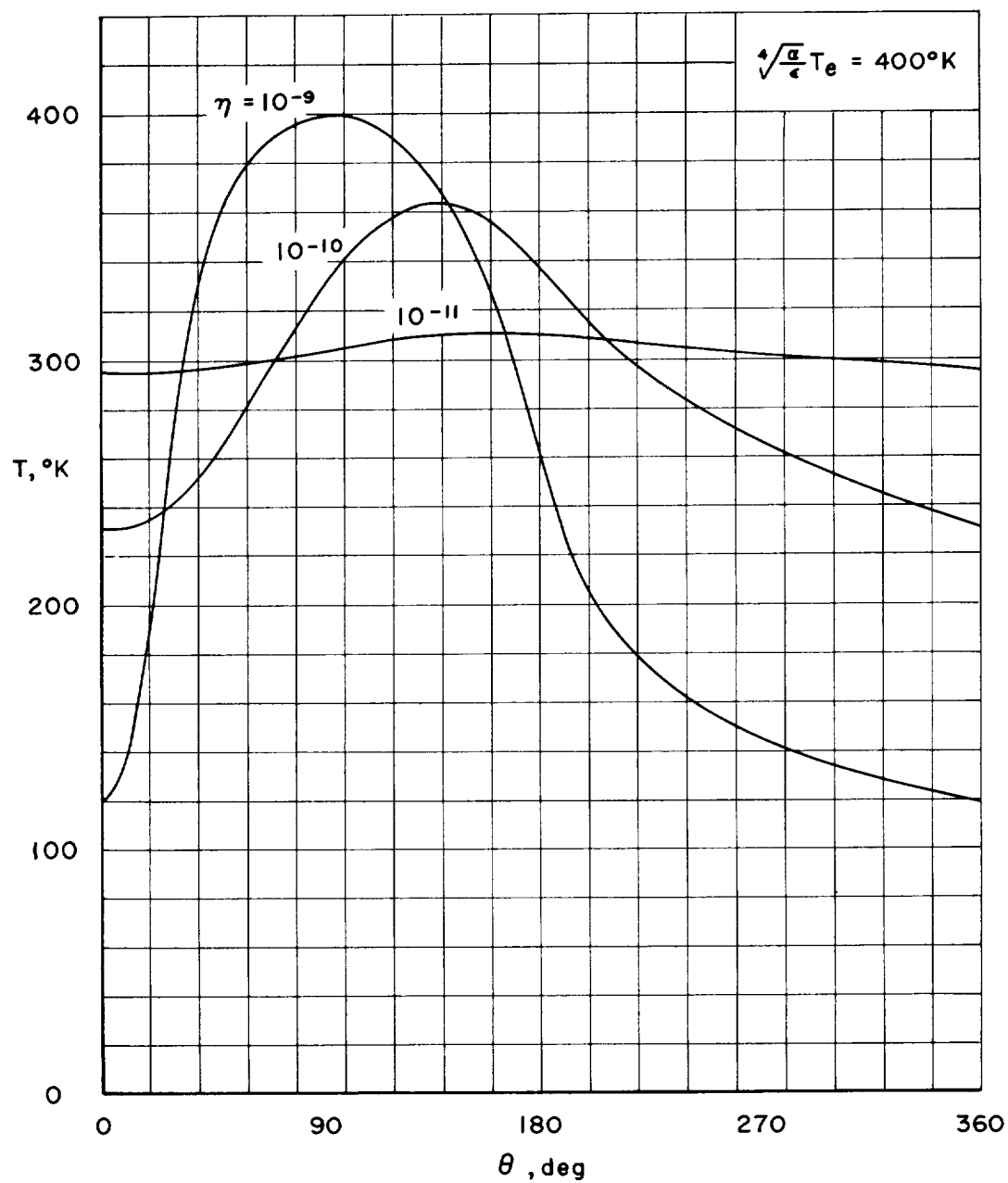
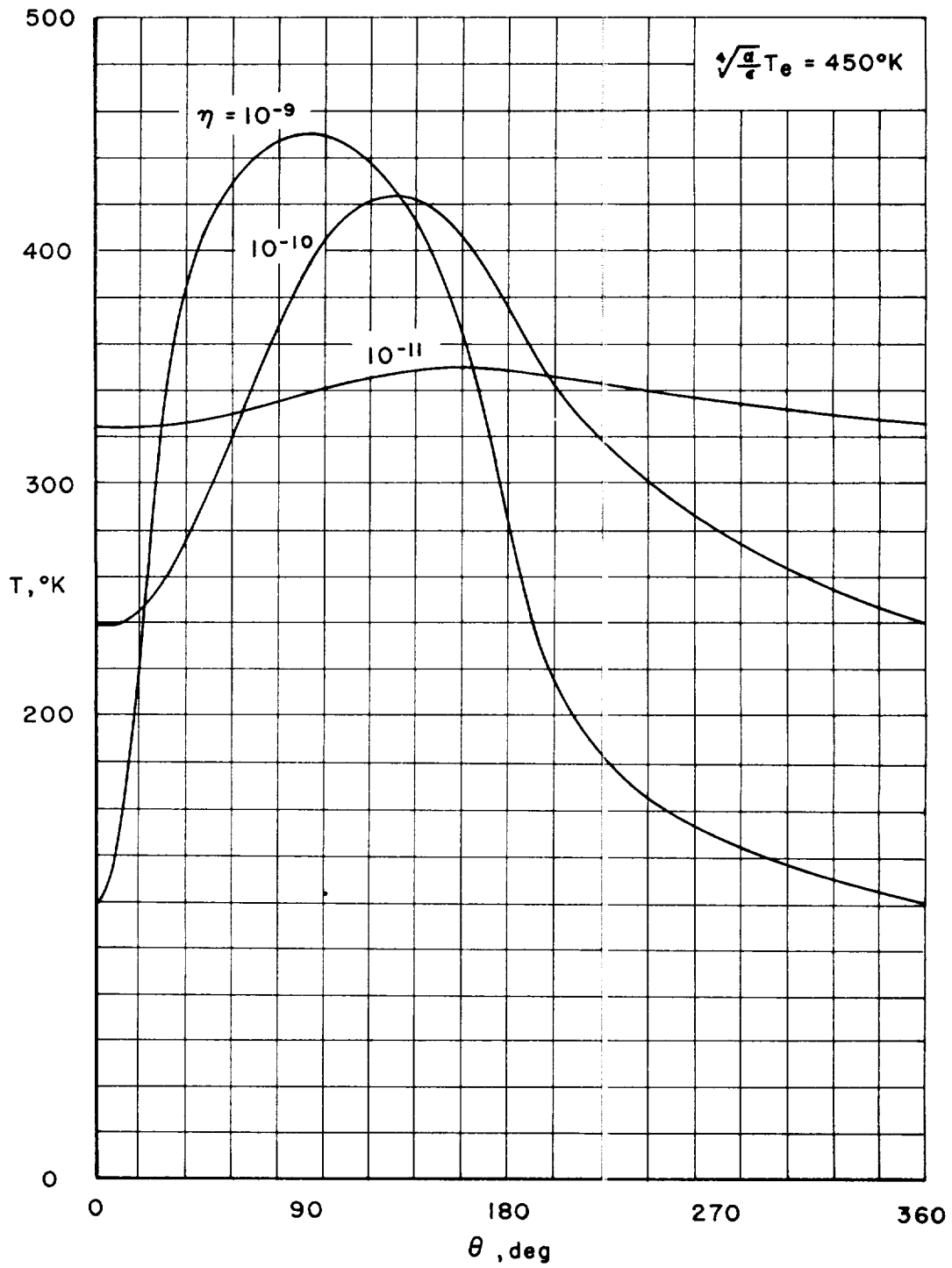
(b) Section through dA .

Figure 2.- Sketch of cylinder composed of capacitor sections of solid dielectric film.



(a) $(\alpha/\epsilon)^{1/4} T_e = 400^\circ\text{K}$

Figure 3.- The steady state variation of temperature with angular position for a rotating dielectric cylinder.



(b) $(\alpha/\epsilon)^{1/4} T_e = 450^{\circ}\text{K}$

Figure 3.- Concluded.

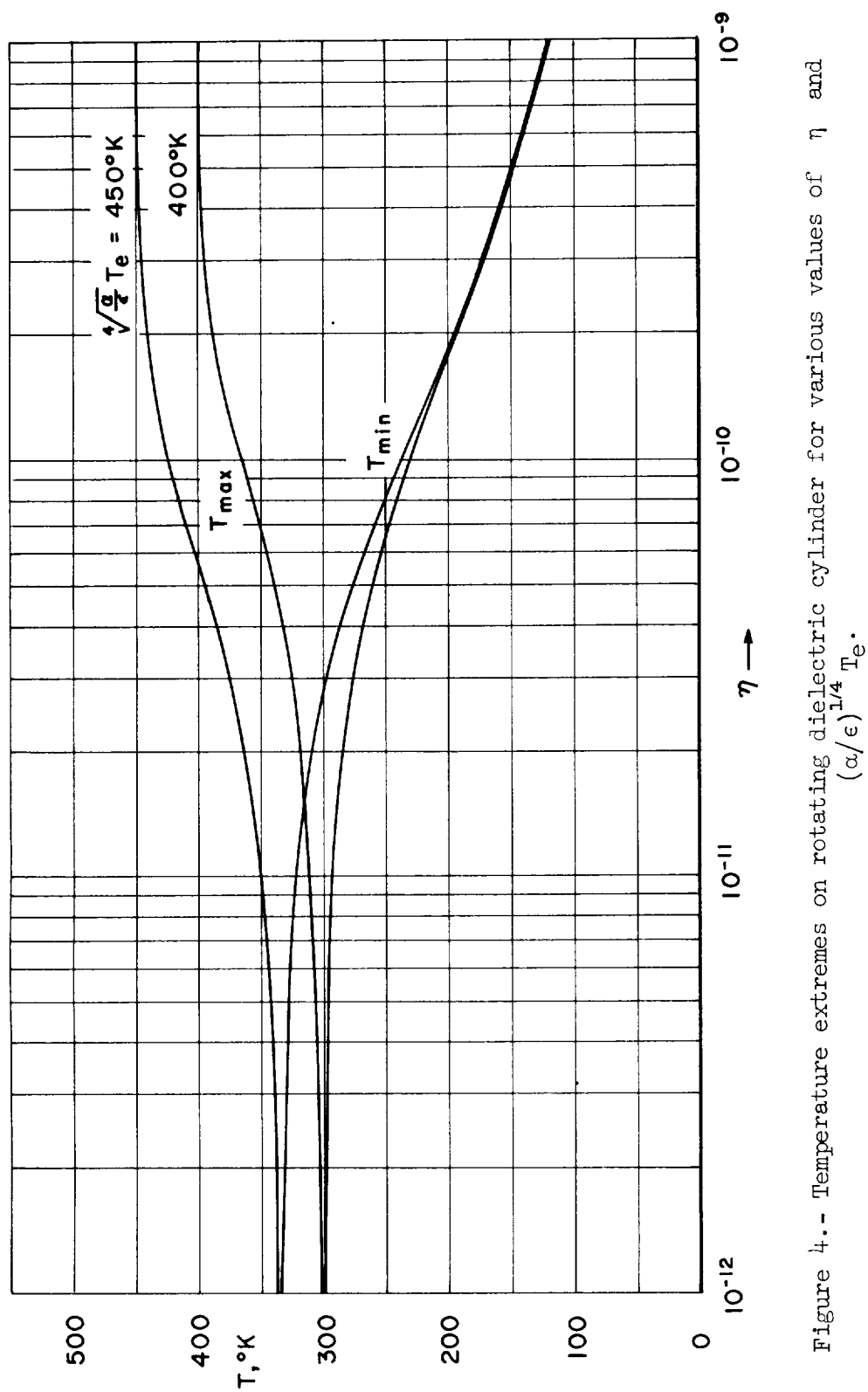


Figure 4.- Temperature extremes on rotating dielectric cylinder for various values of η and $(\alpha/\epsilon)^{1/4} T_e$.

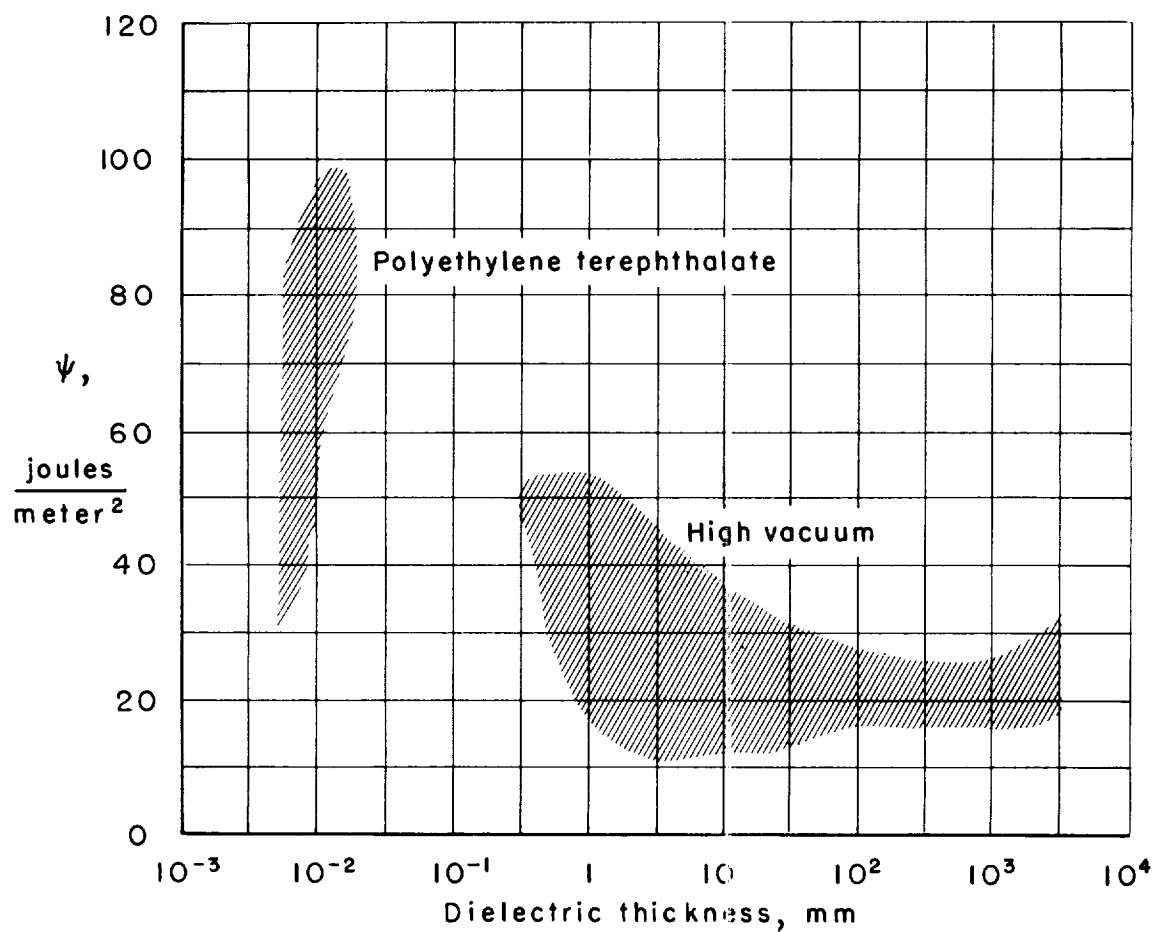


Figure 5.- The energy storage capability of parallel-plate capacitors with polyethylene terephthalate and with high-vacuum dielectric.

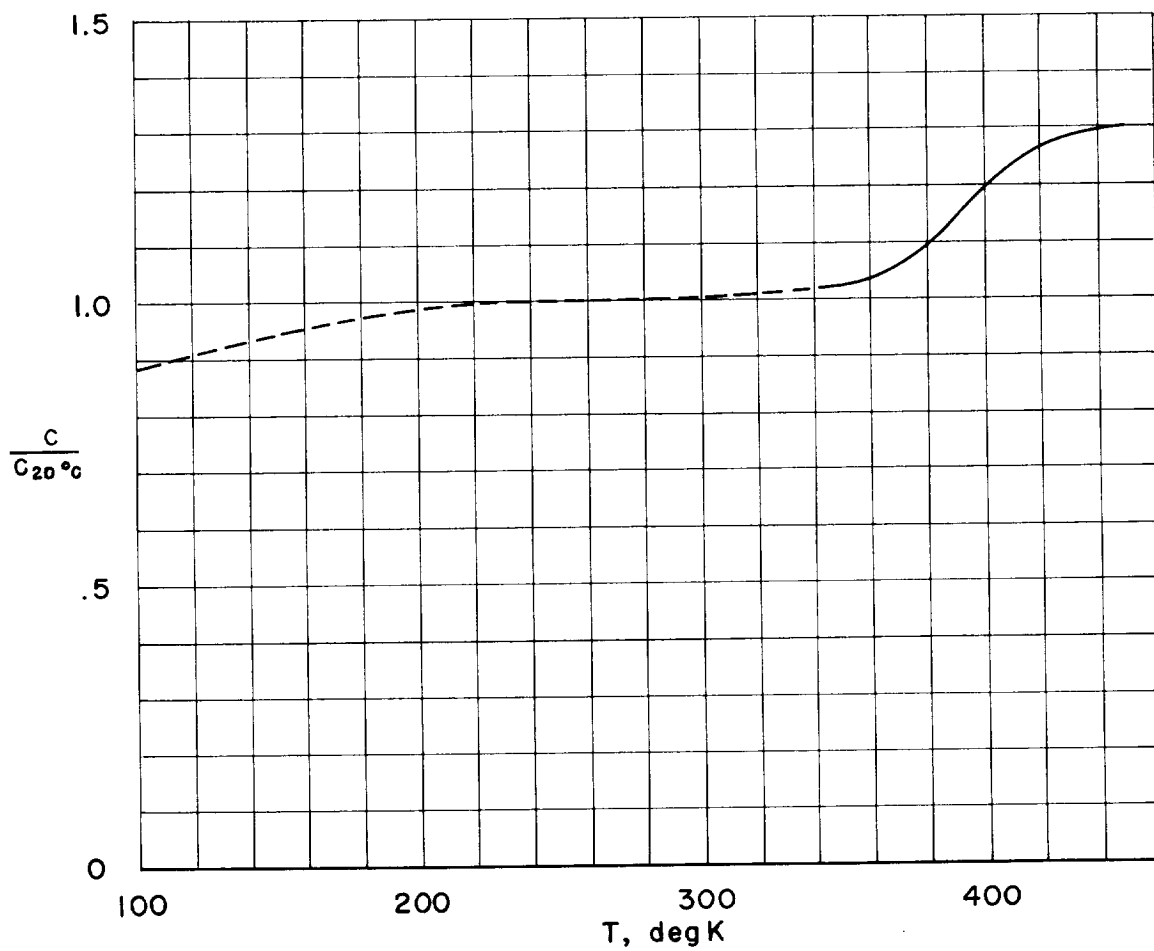


Figure 6.- The variation of capacitance with temperature for a parallel-plate capacitor with polyethylene terephthalate dielectric.

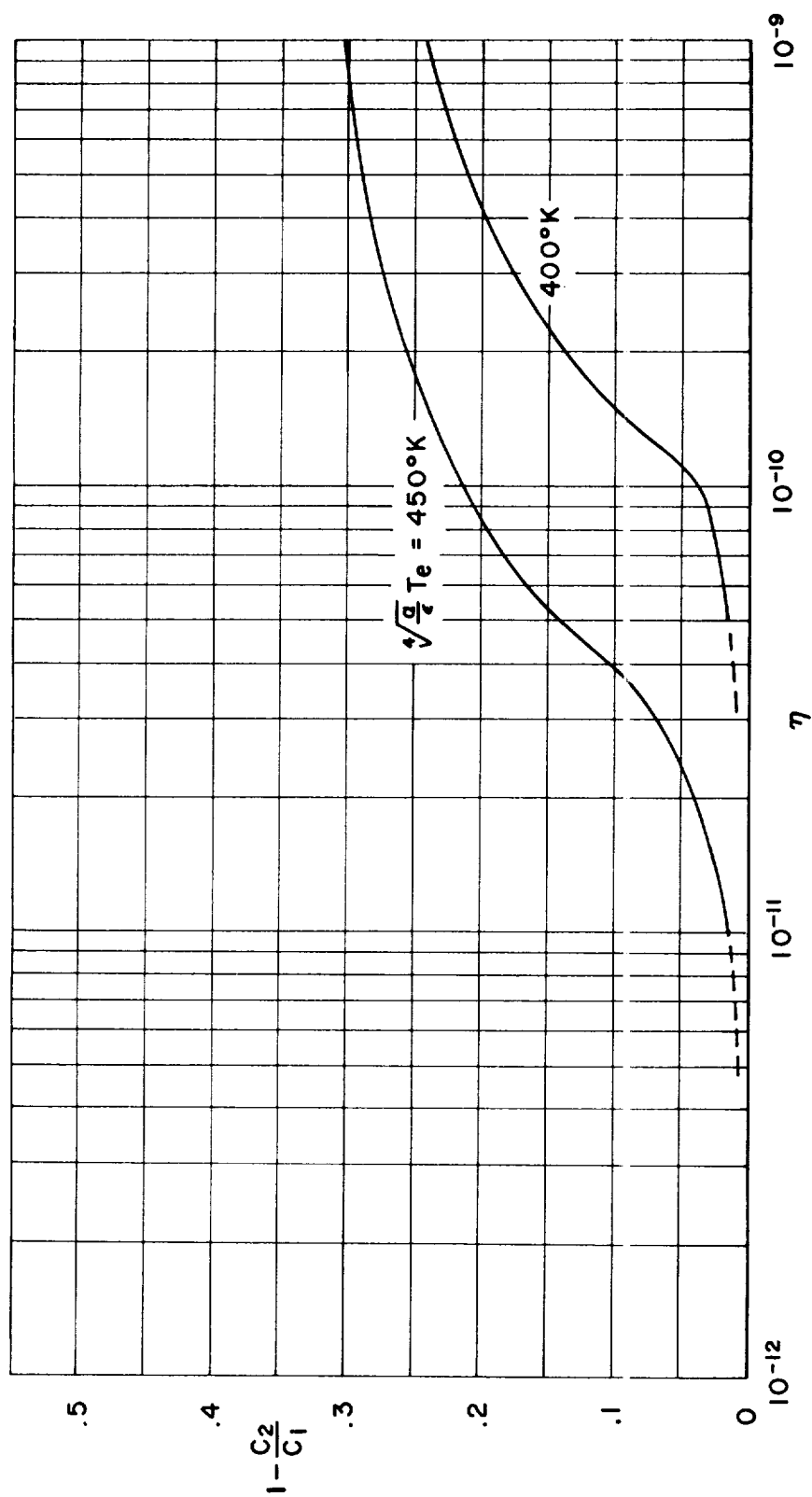


Figure 7.- The variation of $1 - (C_2/C_1)$ with η for a rotating cylindrical capacitor with polyethylene terephthalate dielectric at two values of $(\alpha/\epsilon)^{1/4}T_e$.

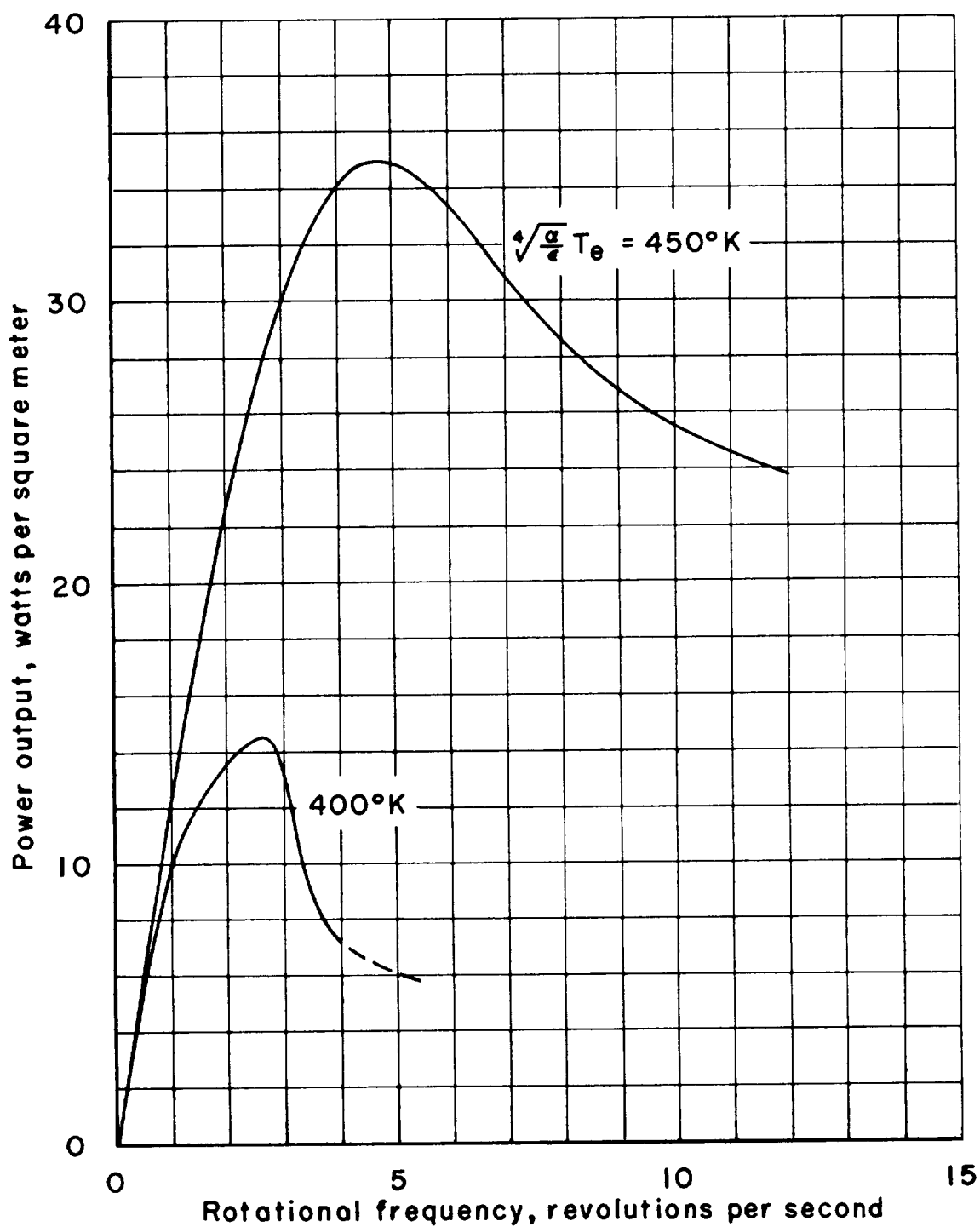


Figure 8.- The variation of power developed per unit area of capacitor with rotational frequency for a rotating cylindrical capacitor generator with polyethylene terephthalate dielectric at two values of $(\alpha/\epsilon)^{1/4} T_e$.

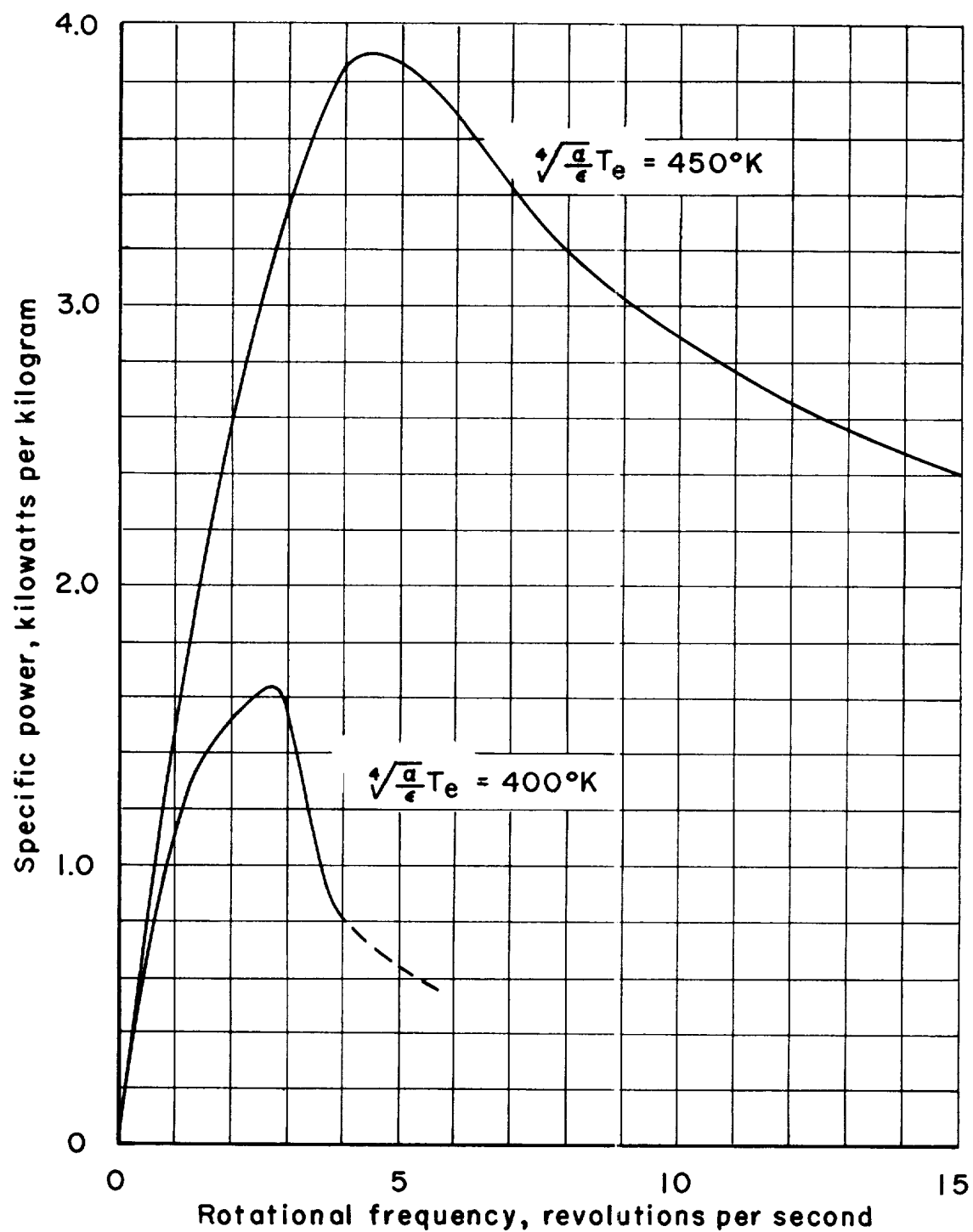


Figure 9.- The variation of the specific power β' with rotation frequency for a rotating cylindrical capacitor generator with polyethylene terephthalate dielectric at two values of $(\alpha/\epsilon)^{1/4} T_e$.

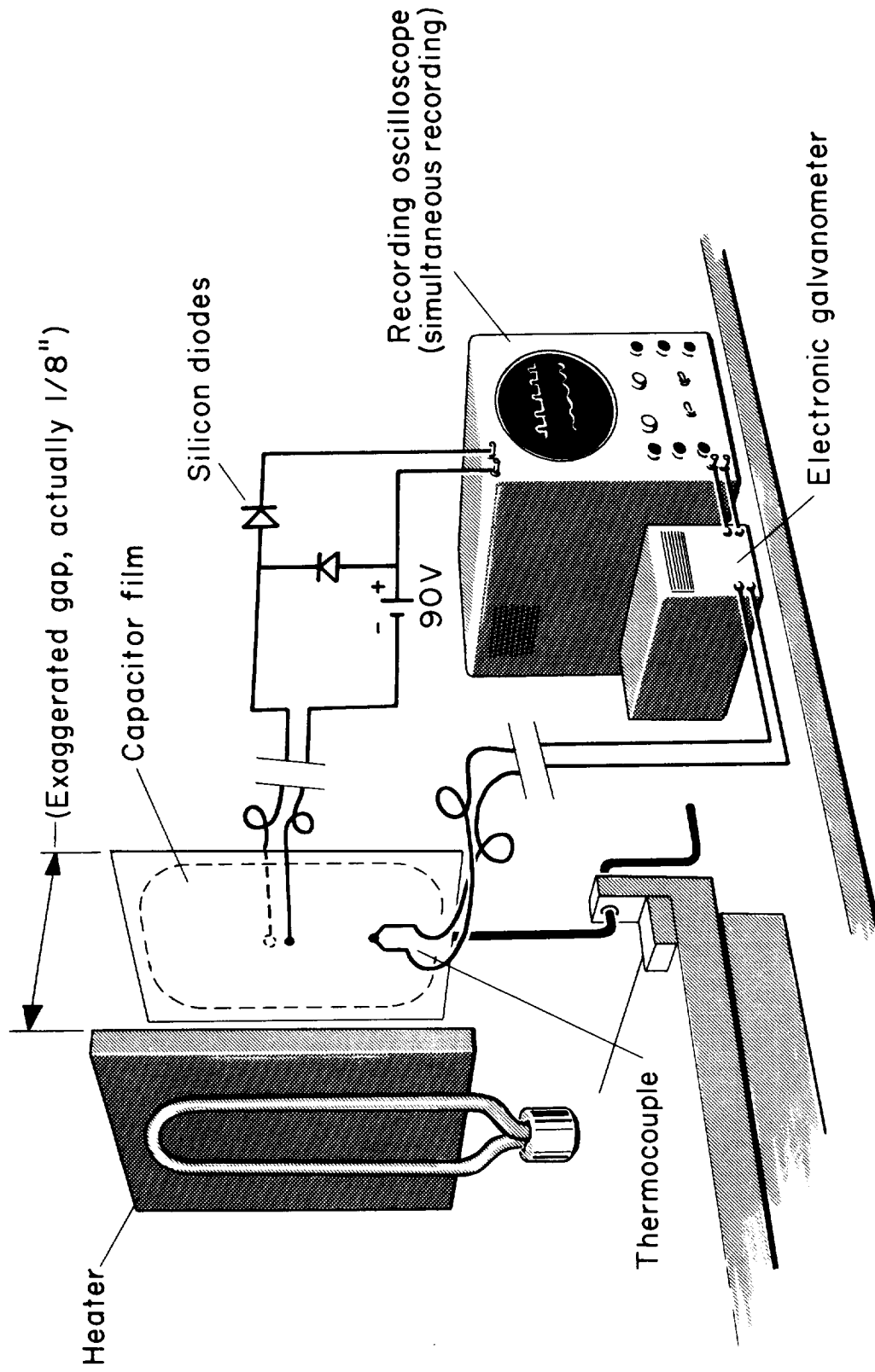


Figure 10.- Sketch of experimental arrangement to demonstrate thermoelectrostatic power generation.

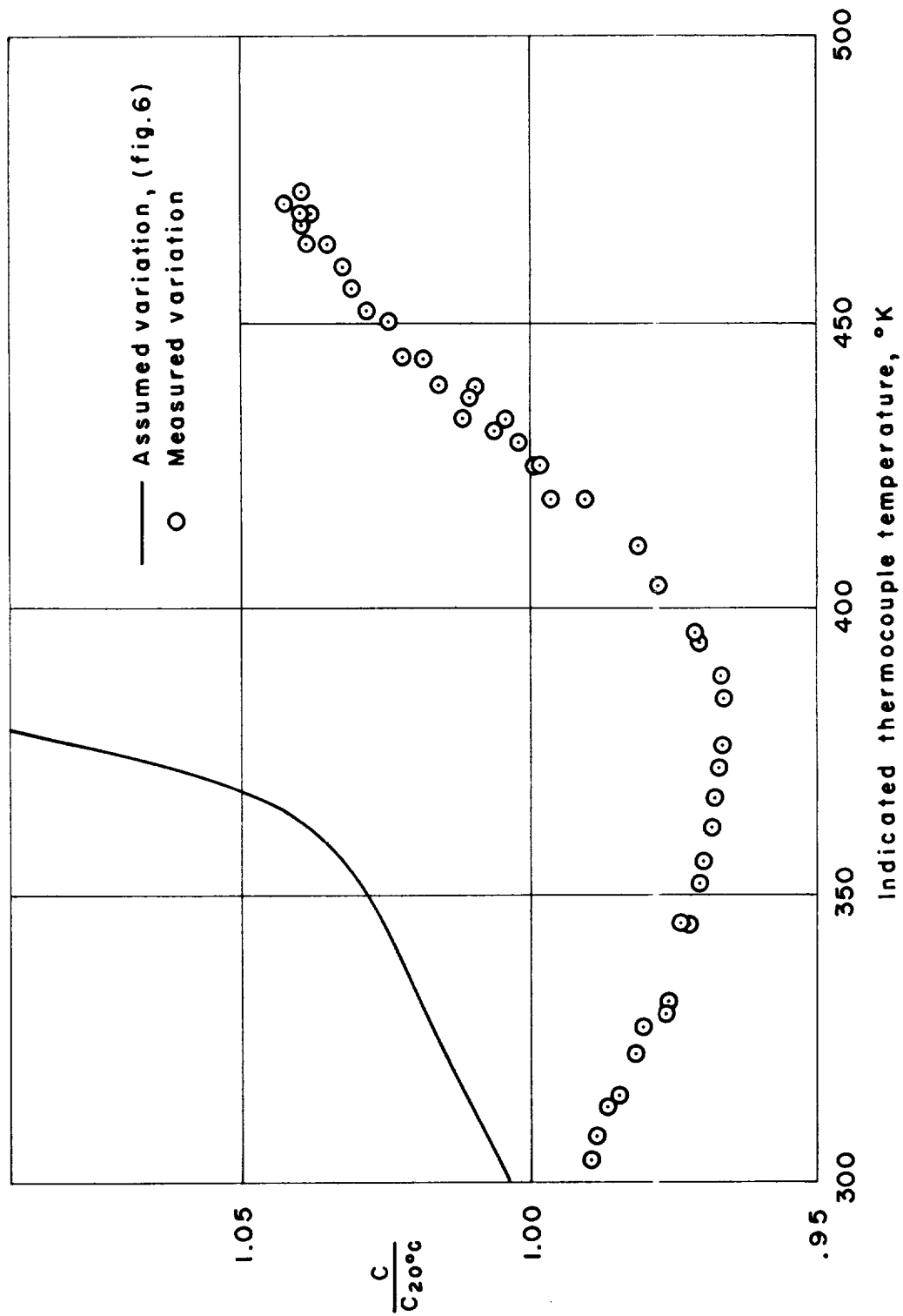


Figure 11.- Variation of capacitance with temperature of a section of polyethylene terephthalate capacitor film used in thermoelectrostatic power generation tests.

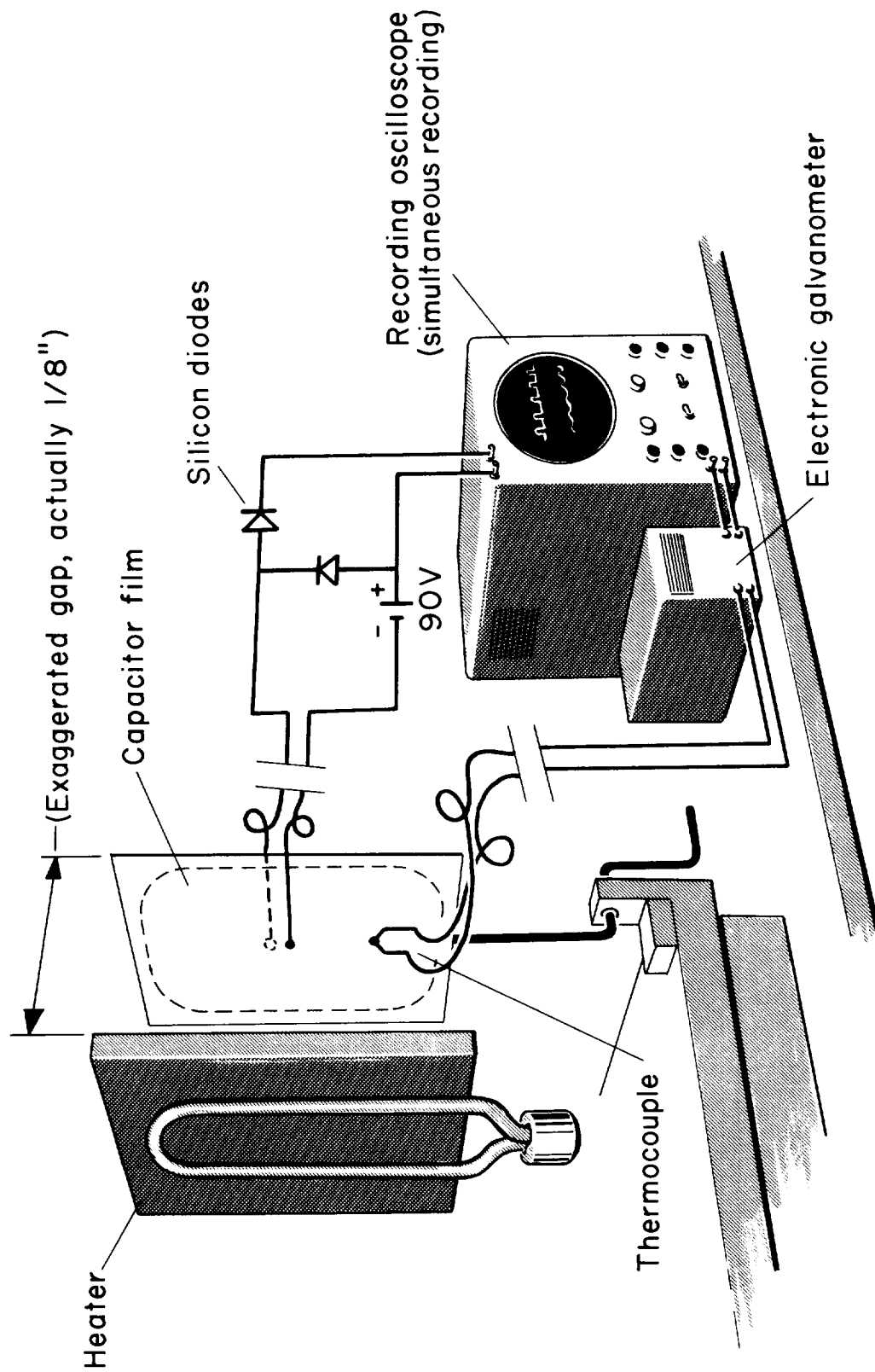


Figure 10.- Sketch of experimental arrangement to demonstrate thermoelectrostatic power generation.

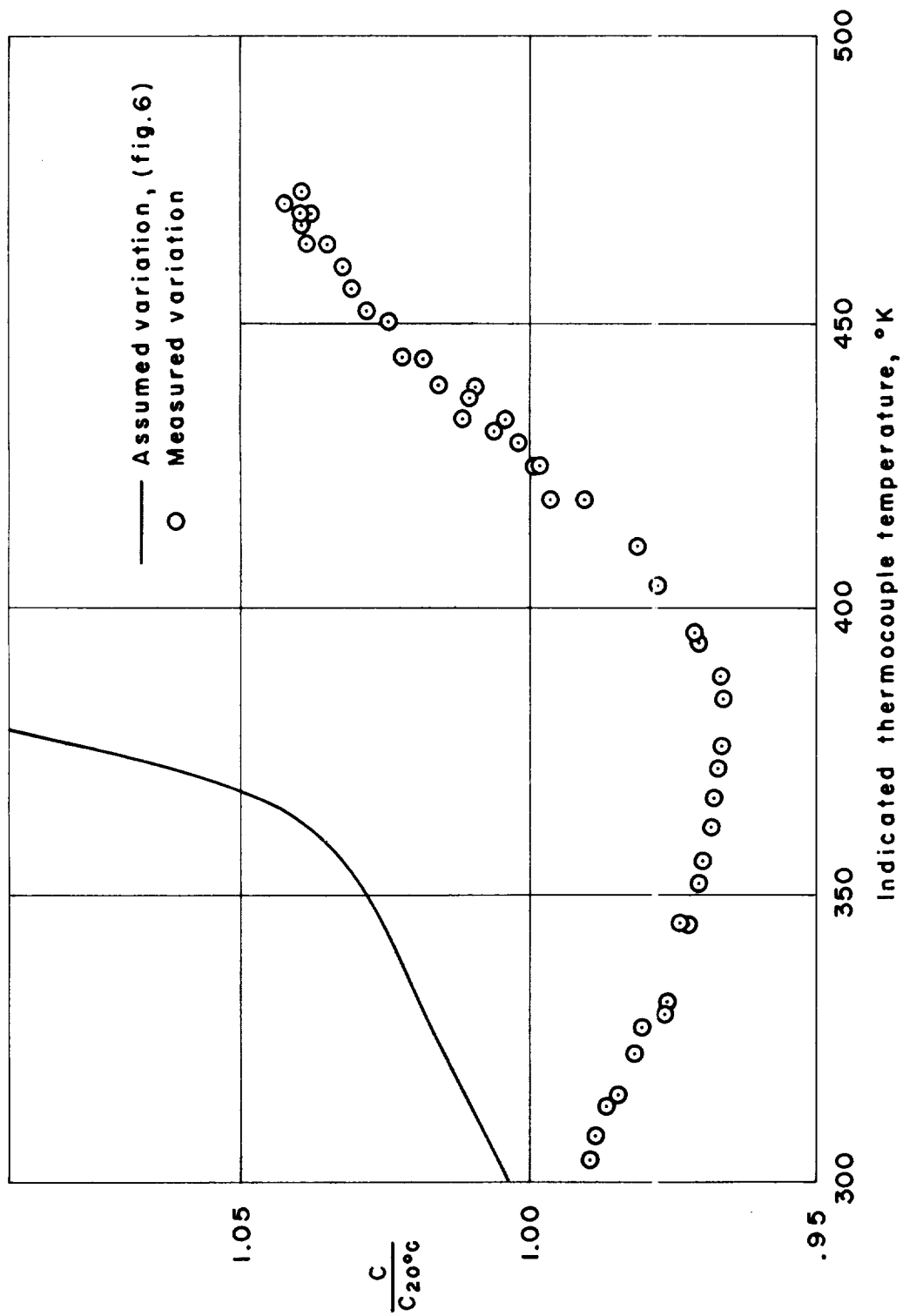


Figure 11.- Variation of capacitance with temperature of a section of polyethylene terephthalate capacitor film used in thermoelectrostatic power generation tests.

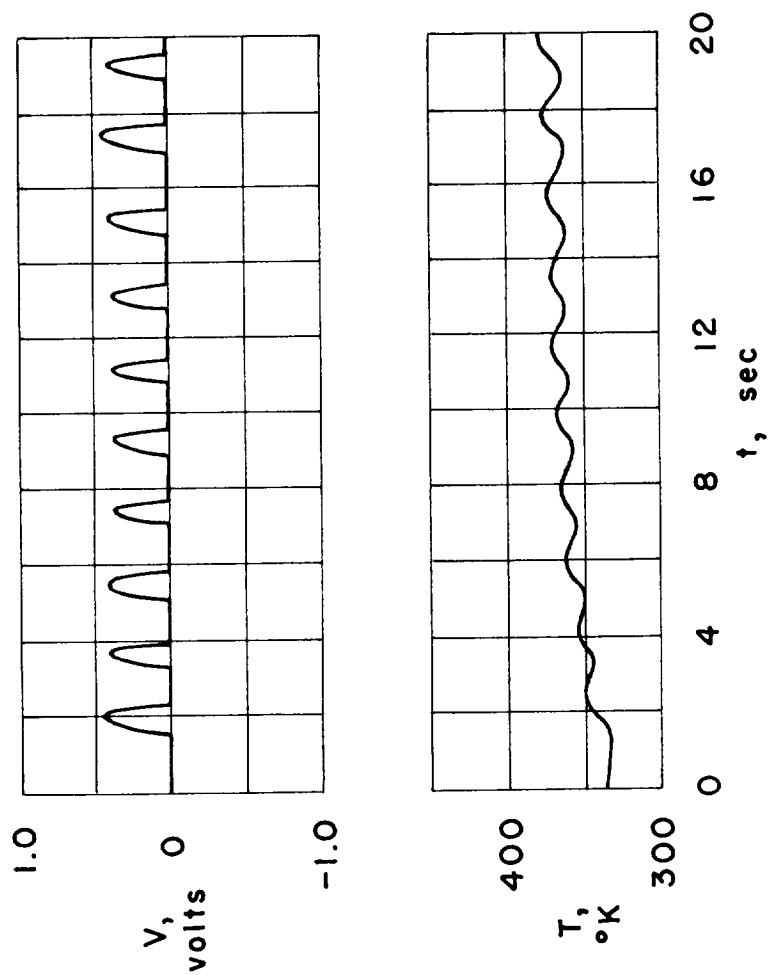


Figure 12.- The variation of generated voltage and thermocouple temperature with time during thermoelectrostatic power generation test.

<p>NASA TN D-336 National Aeronautics and Space Administration. AN EXPLORATORY STUDY OF THERMOELECTRO- STATIC POWER GENERATION FOR SPACE FLIGHT APPLICATIONS. Benjamin H. Beam. October 1960. 35p. OTS price, \$1.00. (NASA TECHNICAL NOTE D-336)</p> <p>A study has been made of a process in which a solar heating cycle is combined with an electrostatic cycle for generating electrical power for space vehicle applications. The power unit, referred to as a thermoelectrostatic generator, is a thin film capacitor alternately heated by solar radiation and cooled by radiant emission. Estimates are included of the performance of this type of device in space in the vicinity of earth. Results of an experiment to illustrate the principle are described.</p> <p>Copies obtainable from NASA, Washington</p>	<p>I. Beam, Benjamin H. II. NASA TN D-336 (Initial NASA distribution: 35, Power sources, supplementary.)</p> <p>NASA</p>	<p>NASA TN D-336 National Aeronautics and Space Administration. AN EXPLORATORY STUDY OF THERMOELECTRO- STATIC POWER GENERATION FOR SPACE FLIGHT APPLICATIONS. Benjamin H. Beam. October 1960. 35p. OTS price, \$1.00. (NASA TECHNICAL NOTE D-336)</p> <p>A study has been made of a process in which a solar heating cycle is combined with an electrostatic cycle for generating electrical power for space vehicle applications. The power unit, referred to as a thermoelectrostatic generator, is a thin film capacitor alternately heated by solar radiation and cooled by radiant emission. Estimates are included of the performance of this type of device in space in the vicinity of earth. Results of an experiment to illustrate the principle are described.</p> <p>Copies obtainable from NASA, Washington</p>	<p>I. Beam, Benjamin H. II. NASA TN D-336 (Initial NASA distribution: 35, Power sources, supplementary.)</p> <p>NASA</p>
<p>NASA TN D-336 National Aeronautics and Space Administration. AN EXPLORATORY STUDY OF THERMOELECTRO- STATIC POWER GENERATION FOR SPACE FLIGHT APPLICATIONS. Benjamin H. Beam. October 1960. 35p. OTS price, \$1.00. (NASA TECHNICAL NOTE D-336)</p> <p>A study has been made of a process in which a solar heating cycle is combined with an electrostatic cycle for generating electrical power for space vehicle applications. The power unit, referred to as a thermoelectrostatic generator, is a thin film capacitor alternately heated by solar radiation and cooled by radiant emission. Estimates are included of the performance of this type of device in space in the vicinity of earth. Results of an experiment to illustrate the principle are described.</p> <p>Copies obtainable from NASA, Washington</p>	<p>I. Beam, Benjamin H. II. NASA TN D-336 (Initial NASA distribution: 35, Power sources, supplementary.)</p> <p>NASA</p>	<p>NASA TN D-336 National Aeronautics and Space Administration. AN EXPLORATORY STUDY OF THERMOELECTRO- STATIC POWER GENERATION FOR SPACE FLIGHT APPLICATIONS. Benjamin H. Beam. October 1960. 35p. OTS price, \$1.00. (NASA TECHNICAL NOTE D-336)</p> <p>A study has been made of a process in which a solar heating cycle is combined with an electrostatic cycle for generating electrical power for space vehicle applications. The power unit, referred to as a thermoelectrostatic generator, is a thin film capacitor alternately heated by solar radiation and cooled by radiant emission. Estimates are included of the performance of this type of device in space in the vicinity of earth. Results of an experiment to illustrate the principle are described.</p> <p>Copies obtainable from NASA, Washington</p>	<p>I. Beam, Benjamin H. II. NASA TN D-336 (Initial NASA distribution: 35, Power sources, supplementary.)</p> <p>NASA</p>

